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Interaction of Hydraulic Structures with Air, Water, and Rock: The Challenge of Researchers and Designers

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KEYNOTE - EXTENDED ABSTRACT

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1. THE IMPORTANCE OF HYDRAULIC STRUCTURES AND SCHEMES FOR THE WORLD ECONOMY

Since the last ten years, financial crisis has strongly impacted the global economy, which was mainly the result of uncontrolled financial speculations at the stock markets highlighted by the revelations regarding offshore companies. Fortunately, the field of construction of large infrastructures, such as hydraulic schemes, has been left relatively untouched by this crisis. In order to stimulate their economies, many governments across the world have injected significant sums into sustainable infrastructures development.

This progress in the field of hydraulic structures and schemes is not astonishing since it has to be kept in mind that the soundness of the world economy is founded mainly on investments and particularly by the creation of infrastructures. Among the last ones, hydraulic schemes play an important role. During several thousand years, man has continuously developed techniques to use water and at the same time to protect himself against water. History shows that the economic prosperity of a society and its cultural wealth have always been closely related to the level of the development of the hydraulic schemes (Schleiss 2000).

The term *hydraulic schemes* includes all measures and human interventions aiming to the control and exploitation of the water cycle. A vital element of our environment, water also presents an important destructive potential. Thus, hydraulic schemes can be divided, according to their objectives, into two groups (Fig. 1):

- schemes for water utilization
- schemes for protection against water

The hydraulic structures designed for water utilization are multipurpose, ensuring water supply, irrigation, hydropower production, and navigation. The structures designed for protection against water are also used for sewage treatment, drainage, flood protection, and erosion protection measures.



Figure 1. Application of hydraulic structures and schemes (Schleiss 2000)

Hydraulic structures can be grouped as follows:

- Storage structures: water supply reservoirs, artificial lakes created by dams, flood retention basins, a.s.o.
- Withdrawal structures: intakes at lakes and rivers, weirs, ogee crests, desilting basins, orifices, a.s.o.
- Conveying and diversion structures: channels, galleries, pressure tunnels and shafts, surge tanks, chutes, bank and bed erosion protections, a.s.o.
- Restitution and energy dissipation structures: stilling basins, plunge pools, flip buckets, vortex and drop shafts, a.s.o.
- Appurtenant hydraulic structures of dams: spillways, bottom outlets, river diversion channels and tunnels, a.s.o.
- Special structures: siphons, aqueducts, a.s.o.

2. CHALLENGES IN THE WORLDWIDE DEVELOPMENT OF HYDRAULIC STRUCTURES AND SCHEMES

The major problems of the world population in this century will certainly be the safe supply of ecological and renewable energy and the supply of good quality water and a sufficient quantity in order to fight against famine, poverty, and disease in the world. These problems must be solved, above all, by investments in the development of new hydraulic structures and schemes, as well as in their maintenance and refurbishment, which is briefly discussed in the following sections.

2.1. Water for Domestic, Industrial, and Agricultural Use

At the beginning of the 21st century, water supply and sanitation services left much to be desired; two thirds of the world population still suffered from the lack of safe water (insufficient quantity) or from the lack of safe sanitation (inappropriate quality). Besides harnessing available resources and improving management of existing resources, the usable potential has to be increased by hydraulic schemes mainly for storage and transportation of water. Even in developed countries, failure of sewer systems due to insufficient hydraulic design causes flooding and pollution of adjacent areas.

2.2. Irrigation

An important part of the world population is still threatened with famine. This risk could be considerably lessened by the irrigation of arid areas not cultivable today. For an efficient irrigation, the creation of reservoirs and the construction of hydraulic structures, such as dams, waterways, and transfer system, as well as restitution structures is absolutely necessary. Furthermore, climate change will contribute to the diminution of today's arable lands in some areas. It has to be feared that the lack of freshwater could be an increasing source of local wars in this century.

2.3. Hydropower and Electricity Production

Since 1950, the growth of the hydropower production has strongly accelerated, a tendency that still continues today. All energy scenarios forecast that the speed of the development of hydropower in the next 50 years will be equal to that of the last 50 years. Less than 20% of the technically feasible hydropower potential has been developed worldwide so far. In South America, only one third of the economically feasible potential is in operation; in Asia (including Russia and Turkey), it is only one fifth. In Africa, a very small portion, namely about 7%, of the economically feasible potential is exploited today. However, in Europe more than 70% and in North America more than 75% of this potential are used. The worldwide remaining economically feasible hydro potential would be high enough to replace the generation by nuclear power plants as well as an important part of the electricity produced by fossil fuels. Furthermore, hydropower from storage schemes can regulate the high volatile production of such new renewable energies as wind and solar.

2.4. Navigation

Most of the goods exchanged and their transportation in the world are ensured by sea and river navigation. This will also be the case in the future as the transportation of goods by road has already reached, in some regions, its bearable limits. There remains a considerable amount of work to be done in the field of navigation, especially in regions where the rivers are not thoroughly navigable. To allow navigation, the construction of hydraulic structures such as dams, canals, ship locks, and harbors is necessary.

2.5. Flood Protection

The population growth combined with the greenhouse effect considerably increases the risk of floods including tsunamis with the danger of disastrous damages as experienced several times recently. Therefore, flood protection measures are an important application of hydraulic structures and become more and more vital for many regions of the world, mainly for densely populated areas.

Concluding this list of applications of hydraulic structures, it is not exaggerated to say that hydraulic schemes will be of fundamental importance in the development of the world society since they can satisfy the vital needs of water-energy-food, and this respecting the environment and the sustainable development of resources.

3. RESEARCH CHALLENGES IN THE FIELD OF HYDRAULIC STRUCTURES AND SYSTEMS

Although a classic branch of civil engineering already theoretically advanced, hydraulic engineering still presents research challenges ensuing from varied reasons. The arise of new measuring and computational capabilities allow the assessment of variables with more detail and precision; a deeper insight in the mechanics of the flows is now possible, allowing a breakthrough on the interpretation of results, which, in the fields of research covered by hydraulic engineering, ensue seldom from empirical approaches based on bulk observations, practical assumptions, or inference from similar studies. Research challenges arise also from new needs claimed by the society, related

mainly to economic (need for optimization and upgrading of water resources exploitation), safety (increased public awareness of the risk associated with built infrastructures and natural elements), and ecologic (increased public awareness on environmental conservation) concerns.

The construction of new and the rehabilitation of existing infrastructure for the use of water and protection against its natural hazards will be a main challenge all over the world. Since the hydraulic schemes have to be realized in a more complex environment, the design and implementation of such schemes are much further demanding, and research is required to answer complex questions.

Hydraulic schemes are in interaction with the environment where, physically spoken, interaction of structures with water, air, and underground is a main issue. This interaction involves multi-phase flows (water, air, sediment) in a 3D environment bounded by complex structures. Even if the numerical models have been strongly improved over the last decade, and if this progress will continue, there will always be new complex problems, which have to be assessed by physical modelling. Furthermore, the latter will always be required to further develop and validate the numerical models. Experience over the last 20 years showed that in parallel with a strong development of numerical models and simulations, the demand in physical modelling was continuing to grow. Today, high competences in physical modelling combined with advanced measurement technologies are required which need a long experience and development in the hydraulic laboratories.

4. THE CHALLENGE TO ASSESS THE INTERACTIONS OF HYDRAULIC STRUCTURES WITH AIR, WATER, AND ROCK

The interaction of hydraulic structures with air, water, and rock results often at interface problems between hydraulic engineering on one side and geotechnical and structural engineering on the other side. These interface problems have to be treated with an interdisciplinary approach, which should be led by the hydraulic engineer.

In the following sections, the challenges for researchers and designers when treating such interface problems involving air, water, and rock are highlighted with some examples.

4.1. Design of Pervious Pressure Tunnel Linings

Pressure tunnels that are not steel lined or not sealed with plastic membranes are essentially permeable. Even not cracked concrete linings are not absolutely tight. Reinforced concrete linings crack under internal water pressure. The task of the reinforcement is to distribute the cracks in such a way that the crack widths remain below a certain limit value. A seepage flow through the lining into the rock inevitably results in the case of permeable linings. The corresponding seepage forces affect both the deformation of the lining and rock. In contrast to an absolutely tight lining, the internal water pressure thus acts both as a uniformly distributed load at the inner side of the lining as well as a hydraulic body force inside the lining and rock. This body force resulting from the hydraulic gradient of the seepage flow causes deformations, which exert an effect on the lining and rock mainly in the form of a change in the crack and fissure widths.

This results in a change in their permeability, which in turn influences the seepage flow forces. Consequently, the mechanical and hydraulic states of a permeable waterway system mutually influence each other through hydraulic-mechanical interactions, as is shown in Figure 2. In order to take this physical characteristic of permeable linings sufficiently into account, the following must be considered when determining stresses and deformations in lining and rock (Schleiss, 1986, 1988):

- forces caused by seepage flow through the lining into the rock (or vice versa) = statics of porous media
- changes in permeability due to lining and rock deformations = rock/groundwater hydraulics

The influence of seepage flow in concrete lining and rock on the design of permeable pressure tunnels is considerable and cannot be neglected in the design (Schleiss 1986, 1988, 1997).

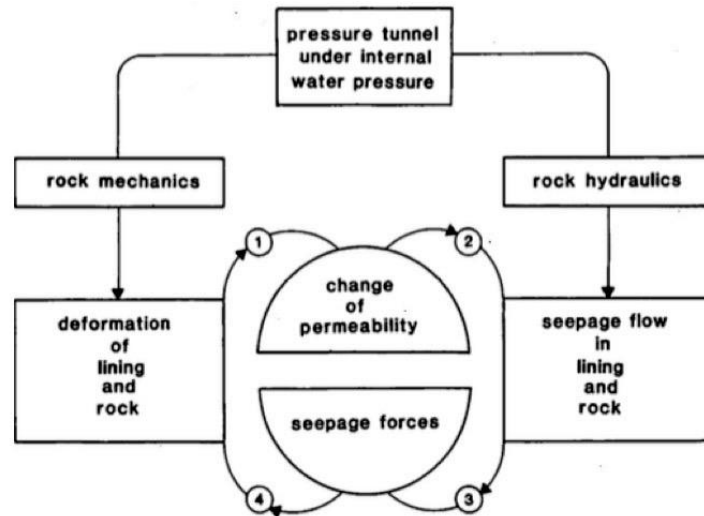


Figure 2. Hydraulic-mechanical interactions and pervious pressure tunnels (Schleiss, 1988)

4.2. Pressure Relief Valves for Protection of Steel-lined Pressure Shafts against Buckling during Emptying

Using high-strength steels for pressure shafts and tunnel liners and taking into account significant rock mass participation allows the design of comparatively thin steel liners in hydropower projects. Nevertheless, during emptying of the waterways, these steel linings may be endangered by buckling. Compared with traditional measures such as increased steel liner thickness and stiffeners, pressure relief valves are a very economical solution for the protection of steel liners against critical external pressure and, therefore, buckling during emptying. A calculation procedure has been developed for the design of the required number and arrangement of pressure relief valves, and this has been used successfully in practice (Schleiss and Manso 2012). Systematic model tests enabled the assumptions of the design method to be verified. The pressure relief valves in the steel liner have to drain the seepage flow from the rock mass in such a way that the external water pressure does not exceed the tolerable value for a certain steel liner thickness. Assuming radial-symmetrical permeability conditions, the discharge through the pressure relief valves is influenced by the head losses of the seepage flow across the a) far field rock mass; b) grouted or loosened rock zone around the pressure shaft or tunnel (if present); c) backfill concrete (non-reinforced, cracked); d) gap between steel liner and backfill concrete (opening depends on external water pressure); e) pressure relief valves. Since the opening of the gap between the steel liner and the backfill concrete depends on the external water pressure, a mechanical hydraulically-coupled system is obtained, which has to be solved with an iterative approach.

4.3. Interaction of Bend Flow in a Channel with Bank Roughness, Bed Morphology and Air Bubble Screens

Practical experience with flood protection projects showed that the scour along outer bank protection walls can be considerably reduced by placing macro-roughness on the bank protection wall. This allows for the reduction of the depth of the foundations, which, in turn, has a reducing impact on the cost of the project. In the framework of a research project, systematic tests were performed to establish the basis for dimensioning vertical ribs, which served as macro-roughness (Hersberger et al. 2016). Experiments showed that the macro-rough outer bank changed considerably the bed morphology under equilibrium conditions. Ribs, appropriately placed along the outer wall, may reduce the maximum scour depth up to 40% in comparison with the scour depth along a smooth (outer) wall. The two prominent scour holes in a 90° bend almost disappear and the erosion is distributed over the whole bend.

Other experiments in a laboratory flume demonstrated that a bubble screen along the outer bank of curved channel can modify the flow patterns and the bed morphology, i.e. reduce bend scour under conditions of live-bed sediment transport and subcritical flow (Dugué et al. 2013, 2015). Air bubbles generated by a pressurized porous tube situated on the bed can entrain the surrounding water and induce a secondary flow perpendicular to the porous tube. In the investigated range of conditions, based on both theoretical considerations and experimental results, the vertical velocity of the entrained water was estimated to be about 25% of the rising velocity of the air bubbles, which defines the water entrainment efficiency. The bubble-induced secondary flow can redistribute the pattern of the longitudinal velocity, which results in less scour at the outer and less deposition at the inner channel bank under mobile-bed conditions. Such bubble screen may be a promising mitigation measure to ensure an almost uniform flow depth across bends in navigation channels.

4.4. Interaction of Turbidity Currents in Reservoirs with Fixed and Permeable Obstacles

In order to ensure the sustainable use of man-made reservoirs, the management of sedimentation is a challenge for designers and dam operators. Very often, turbidity currents are the main process for the transport and deposit of suspended sediments in reservoirs. Systematic physical and numerical investigations showed that turbidity currents can be slowed down by obstacles or permeable screens and most of the sediments can be retained upstream of them (Oehy and Schleiss, 2007). For turbidity currents with heights of 10 m to 20 m, as they occur in narrow alpine reservoirs, the obstacle shows efficient blocking if the approaching flow is subcritical and if the height of the obstacle is at least equal to twice the height of the approaching flow. The blocking effect of the permeable screen or geotextile depends mainly on its porosity and is efficient in both sub- and supercritical flows. To obtain a significant blocking effect, the screen should have a height of twice the height of the approaching flow and a porosity smaller than 30%. Fixed obstacles can be built as embankment dams, which should always be submerged during reservoir operation. During each flood event in which a turbidity current occurs, the storage volume upstream of the obstacle is reduced somewhat. The case study in Grimsel reservoir (Oehy and Schleiss, 2001) showed that obstacles with heights of 20m will lose their retaining capacity only after about 50 years. A more sustainable solution could be the construction of several obstacles along the reservoir.

Screens or geotextile curtains have similar applications in reservoirs as obstacles. Nevertheless, compared to embankment dams or concrete walls, the installation of geotextile screens is less time consuming and requires only a short lowering of the reservoir level. Installing several screens in series can increase the sediment retention efficiency. The screens can be made of fiber-reinforced geotextile bands. They can then be fixed at horizontal steel cables spanned over the reservoir valley and/or fixed with vertical steel cables and floats.

4.5. Rock Scour due to High-velocity Jet Impact Downstream of Dams on Rocky River Bed

In the case of high head spillways at dams, one main issue is the challenge of energy dissipation and scour control downstream (Schleiss 2002). High-velocity jets can occur, which are guided by the releasing structures into the tail-water at a certain distance from the dam. At the zone of impact of these high-energy jets, the riverbed will be scoured. Since scour due to plunging jets can reach considerable depth even in rocky river beds, instability of the valley slopes has to be feared, which, in some cases, can endanger the foundation and the abutment of the dam itself. Such scour problems occur especially at concrete dams where the spillways are combined with the dam structure itself, and, consequently, the impact zone of the high-velocity falling jets is relatively close to the dam. Scour in jointed media is a very complex process that has to consider all involved physical parameters which can be related to the three phases: water, rock, and air. Bollaert (2002) measured for the first time the transient pressures in rock joints due to high-velocity jet impact with systematic laboratory tests with and experimental set-up reproducing near prototype conditions and reproduced them in a numerical model. New phenomena could be observed and explained as the reflection and superposition of pressure waves, resonance pressures, and quasi-instantaneous air release and resolution due to pressure drops in the joint. The analysis revealed that the pressure wave velocity is highly influenced by the presence of free air bubbles in the joints. These bubbles can be transported by flow from the plunge pool into the joint but also be released from the water during sudden pressure drop below atmospheric pressure.

In open-end joints, instantaneous net uplift pressures of 0.8 to 1.6 times the incoming kinetic energy of the impacting jet has been measured. Based on the experimental results and the numerical simulation, a new model for the evaluation of the ultimate scour depth has been developed, the so-called Comprehensive Scour Method (CSM), which represents a comprehensive assessment of the two physical processes: hydrodynamic fracturing of closed-end rock joints and dynamic uplift of rock blocks (Bollaert 2002, 2004, Bollaert and Schleiss 2003a, 2003b, 2005). All relevant processes as the characteristics of the free falling jet (velocity and diameter at issuance, initial jet turbulence intensity), the pressure fluctuations at the plunge pool bottom, and the hydrodynamic loading inside rock joints are dealt with and compared with the resistance of the rock against crack propagation. The CSM model was further enhanced by considering geometry of plunge pool and lateral confinement of plunging jet (Manso et al. 2009) as well as the dynamic response of a rock block due to fluid-structure interaction (Federspiel 2011, Asadollahi et al. 2011). In a recent research study, the influence of jet aeration was investigated and implemented in the CSM model (Duarte et al. 2015, 2016).

5. REFERENCES

- Asadollahi, P., F. Tonon, M. Federspiel, M. and A. J. Schleiss, (2011). Prediction of rock block stability and scour depth in plunge pools. *Journal of Hydraulic Research*, 49(5): 750-756.
- Bollaert, E. (2002). Transient water pressures in joints and formation of rock scour due to high-velocity jet impact. Communication N° 13 of the Laboratory of Hydraulic Constructions (LCH), EPFL, Lausanne. (Ed. By A. Schleiss).
- Bollaert E. and A. J. Schleiss. (2003a). Scour of rock due to the impact of plunging high velocity jets - Part I: A state-of-the-art review. *Journal of Hydraulic Research*, 41(5): 451-464.
- Bollaert E. and A. J. Schleiss. (2003b). Scour of rock due to the impact of plunging high velocity jets. Part II: Experimental results of dynamic pressures at pool bottoms and in one- and two-dimensional closed end rock joints. *Journal of Hydraulic Research*, 41(5): 465-480.
- Bollaert, E. (2004). A comprehensive model to evaluate scour formation in plunge pools. *International Journal of Hydropower and Dams* 11(1): 94-101.
- Bollaert E. and A. J. Schleiss. (2005). Physically based model for evaluation of rock scour due to high-velocity jet impact. *Journal of Hydraulic Engineering ASCE*, March 2005, pp.153-165
- Duarte, R., Schleiss A.J. and Pinheiro, A. (2015). Influence of jet aeration on pressures around a block embedded in a plunge pool bottom". *Environmental Fluid Mechanics*, (15)3, p. 673-693.
- Duarte, R., Schleiss A.J., Pinheiro, A. (2016). Effect of pool confinement on pressures around a block impacted by plunging aerated jets, *Canadian Journal of Civil Engineering*, 43:(3), 201 - 210.
- Dugué, V. , Blanckaert, K. , Chen, Q. , and Schleiss, A. J. (2013). Reduction of bend scour with an air-bubble screen - Morphology and flow patterns. *Int. J. Sediment Res.* , 28 (1) , 15–23.
- Dugué, V., Blanckaert, K., Chen, Q., and Schleiss, A.J. (2015). Influencing Flow Patterns and Bed Morphology in Open Channels and Rivers by Means of an Air-Bubble Screen. *J. Hydraul. Eng.*, 141(2), 04014070.
- Federspiel, M.P.E.A., 2011. Response of an embedded block impacted by high-velocity jets. Communication 47 of Laboratory of Hydraulic Constructions, Lausanne, Switzerland, ISSN 161-1179 (Ed. Schleiss A.).
- Federspiel, M., Bollaert, E., Schleiss, A. J. (2011). Dynamic response of a rock block in a plunge pool due to asymmetrical impact of a high-velocity jet. *Proc. of 34th IAHR World Congress*, 26 June - 1st July 2011, Brisbane, Australia, CD-Rom, ISBN 978-0-85825-868-6, pp. 2404-2411
- Manso, P. A., Bollaert, E. F. R., Schleiss, A. J. (2009) Influence of Plunge Pool Geometry on High-Velocity Jet Impact Pressures and Pressure Propagation inside Fissured Rock Media. *Journal of Hydraulic Engineering*, 135(10): 783-792.
- Oehy C.D., Schleiss, A.J. (2001). Numerical modelling of a turbidity current passing over an obstacle – practical application in the Lake Grimsel, Switzerland. *Proceedings of the 2001 International Symposium on Environmental Hydraulics*, Tempe, 5-8 December 2001, 6 pages, CD-ROM.
- Oehy Ch., Schleiss, A.J. (2007). Control of Turbidity Currents in Reservoirs by Solid and Permeable Obstacles. *Journal of Hydraulic Engineering*, 133(6): 637-648.
- Hersberger, D., Franca, M., and Schleiss, A.J. (2016). Wall-Roughness Effects on Flow and Scouring in Curved Channels with Gravel Beds. *Journal of Hydraulic Engineering*, 10.1061/(ASCE)HY.1943-7900.0001039, 04015032.
- Schleiss A. J. (1986). Design of pressure tunnels. *Water Power and Dam Construction*, 38(5): 21–26

- Schleiss A.J. (1988). Design criteria applied for the lower pressure tunnel of the North Fork Stanislaus River Hydroelectric Project in California. *Rock Mechanics and Rock Engineering*, 21, 161-181.
- Schleiss A. J. (1997). Design of reinforced concrete linings of pressure tunnels and shafts. *Hydropower and Dams*. 4(3): 88–94
- Schleiss A. J. (2000). The importance of hydraulic schemes for sustainable development in the 21st century. *Hydropower and Dams* 7(1): 19 – 24.
- Schleiss, A.J. (2002). Scour evaluation in space and time – the challenge of dam designers, *Proc. of Int. Workshop on Rock Scour due to falling high-velocity jets*, Lausanne, Switzerland, 25-28 September, (Ed. Schleiss and Bollaert), pp 3-22.
- Schleiss, A. J. and Manso P. (2012). Design of pressure relief valves for protection of steel-lined pressure shafts and tunnels against buckling during emptying. *Rock Mechanics and Rock Engineering* 45 (1): 11–20